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Sponsored By Naval Facilities Engineering Command

NCEL Technical Note

Characteristics and Size Reduction of Navy and Municipal Solid Wastes

Cont'd from pg 1

ABSTRACT Characteristics of Navy Solid Wastes (NSW) and Municipal Solid Wastes (MSW) were compared. The former contained more organic compounds and less than one weight percent of flammable or explosive materials. The performances of shear shredder and hammermill shredder on size reduction were examined. The shear shredder processed a larger quantity and variety of solid wastes with a greater rate and availability. The shear shredder also had a significant economical advantage over the hammermill; however, the hammermill produced a finer solid size with a better maintainability.

Keywords: waste management; waste recycling

NAVAL CIVIL ENGINEERING LABORATORY PORT HUENEME CALIFORNIA 93043

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II

METRIC CONVERSION FACTORS

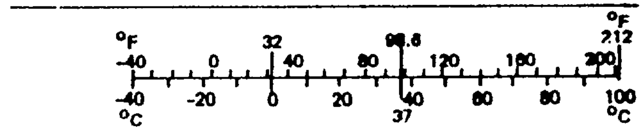
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1. Solid wastes 2. Shredders I. R0371-013-431C

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CONTENTS

INTRODUCTION

The Naval Facilities Engineering Command (NAVFAC) has tasked the Naval Civil Engineering Laboratory (NCEL) to investigate alternate disposal technologies for Navy solid waste (NSW). Besides landfill and incineration, one potential method is to make refuse-derived fuel (RDF) from the solid waste. A prerequisite or benefit to these methods is to reduce the physical size of solid waste.

Several investigators have studied size reduction and classification for solid waste. Trezek ~~(Ref 1)~~[a] conducted laboratory research to characterize the size reduction of municipal solid waste (MSW). Data and results were presented on the relationships between size reduction, grinding speed, moisture content, energy consumption, and feed rate. Also basic considerations for designing solid waste shredders were included. Wilson ~~(Ref 2)~~[a] compiled typical data on waste components, moisture content, volatile substances, and other properties of MSW. Freeman and Capps ~~(Ref 3)~~[a] analyzed the data of NSW and developed → cont'd pg I relationships of bulk density with respect to source and type of NSW.

The work on size reduction of Navy solid wastes was conducted between January and September, 1984. This report includes more pertinent information for solid wastes. The objectives are:

1. To determine the characteristics of NSW and compare with the MSW.

2. To compare the performances of the relatively new shear shredder and the most popular hammermill shredder.

3. To compare the life-cycle costs of the two methods to shred Navy solid waste.

EXPERIMENTATION

Two types of commercial-scale shredders were utilized in this program. The first was a Cedarapids 5096 low-speed, high-torque, rotary shear shredder. The second was a Heil 42-F high speed, vertical shaft hammermill.

Comparisons of the two types of shredders are shown in Table 1. The shear shredder had a feed conveyor, discharge conveyor, and compactor. The two hammermill shredders had individual feed conveyors, but shared a discharge conveyor and compactor.

Tests were conducted at the Charleston County, South Carolina Solid Waste Reduction Center (SWRC). Concurrently ten samples of Navy solid waste from the Charleston Naval Base were analyzed to determine the composition of material and difficult-to-shred or unshreddable materials.

It should be noted that although the overall test lasted 8 months from January to September, 1984, some data were only available for a shorter period due to recording problems. For example, the detailed repair data were only recorded for 6 months and the power consumption data for 5 months.

Throughout the 8-month period, the shear shredder processed four times as much material as the hammermill shredder. The total production during the period was 48,710 tons for the shear shredder and 23,640 tons for the two hammermill shredders. Daily average throughput was 295 tons and 75 tons, respectively. Maximum daily quantities processed were 488 tons versus 150 tons. Ten samples of shredded material were collected from each shredder for size analysis. The samples were dried and then screened through 12-, 8-, 6-, 4-, 2-, 1-, 1/2-, 1/4-, and 1/8-inch sieve series. These samples were also hand-separated into ten compositional categories. Size distributions were calculated for each category and for the total sample.

RESULTS AND DISCUSSION

Density and Composition of NSW

Ten samples were collected from the NSW at Charleston County, SC for analysis. These samples had a total weight of 48,918 pounds. The materials had a bulk density in the trucks of 5.05 lb/ft^3 and a weighted average density of 5.18 lb/ft^3. The densities and compositions are shown in Table 2.

Densities are important factors that are used to convert an easily measured volume to weight. It is interesting to check these data with previous investigations. Freeman and Capps (Ref 3) developed a long term waste characterization by using national average density of the NSW. They employed the survey data of 16 Navy activities gathered by the Naval Environmental Office in 1976 and 1978. Two separate multiple linear regressions were carried out to obtain the NSW densities for 11 sources and 13 types of waste.

The estimated densities for 13 different types of NSW and the statistics are shown in Table 3.

The weighted-average density of the Charleston County, SC, solid wastes can be calculated using the type densities established by Freeman and Capps (Ref 3) and others (Ref 4). The calculations are shown in Table 4. The observed weighted-average density was 139 lb/yd^3 while the calculated weighted-average density was 110 lb/yd^3. The difference is believed to be caused mainly by the site characteristics of the Navy solid wastes. Different Navy sites or activities may perform different missions that lead to different types of solid wastes. However, Freeman and Capp's approach is useful and the "national average density" of the NSW shall become more reliable if more data of different sites are collected.

As shown in Table 2, the composition of NSW from the South Carolina SWRC was divided into five major categories and various smaller categories. The five major categories are organics, inerts/glass, ferrous metals, nonferrous, and miscellaneous. Comparison of the composition of NSW with that of typical MSW (Ref 4) is shown in Table 5. It can be seen

that the organic content of the Navy solid waste found in this study is about 97%. It is in agreement with previous study by Freeman and Capp, but much higher than typical municipal solid waste whose organic materials are about 68%. The miscellaneous category of the NSW includes materials that are considered flammable or explosive; however, the flammable or explosive materials were less than 0.5 percent by weight.

Suitability of NSW to be Shredded

A summary of the unshreddable and difficult-to-shred objects in the Navy waste is shown in Table 6. Of all the Navy material analyzed, the shear shredder was expected to be incapable of shredding 0.04 percent of the waste and to have difficulty shredding an additional 0.21 percent of the waste. For the same waste, the Heil 42-F hammermill was unable to shred 10.41 percent of the waste and had difficulty shredding 4.92 percent more of the waste.

Most of the problems encountered with waste for the hammermill shredder were due to: (1) large size material that could not fit into the shredder feed chute; (2) flexible material that could wrap around the rotor; (3) tough material which could not be rejected through the ballistic ejection chute; and (4) the flammable or explosive material. The problem materials for the shear shredder were nylon webbing, steel steps, and aluminum blocks.

Processing Capacity of Shredders

The average daily throughput rates were determined by maintaining a record of the tons processed through the shredder and the operating hours of the shredder during each daily shift. On Mondays, Tuesdays, Thursdays, and Fridays the normal shift for the plant was 9 hours. On Wednesdays the shift was scheduled for 6 hours due to a decrease in the amount of solid waste collected. There were no weekend operations.

The results of the processing capacities are shown in Table 7. The data does not include days when the equipment was down for repairs and production capacity was zero. The shear shredder processed 48,710 tons and the two hammermills processed 23,640 tons during the analysis period. Average daily processing quantities were 295 tons for the shear shredder and 75 tons for each hammermill.

The average processing capacity for the shear shredder throughout an 8-month period was 68.9 TPH during the time it was actually processing. The capacity dropped to 33 TPH as idle, blockage, repair, and no-fault hours were included. The average processing rate for the hammermills was 16.7 TPH, considering only active processing hours. This dropped to 8 TPH with the addition of idle, blockage, repair, and no-fault hours.

All shredders were processing Navy soild waste for nearly 700 hours over the 8-month period. The shear shredder displayed a capacity four times greater than that for each hammermill, or two times the combined production of the two hammermill shredders.

Composition and Size of Shredded Waste

Average size data from the shear shredder are presented in Table 8. All data from ten samples were used except for those which had a glass

content in excess of 40 percent. Average size data from the hammermill shredder are presented in Table 9. In this case, all the sample data were utilized except one which had nearly 40 percent combined glass and inerts. The results presented are the averaged size and composition of nine discharge samples from each shredder.

Comparing Tables 8 and 9, the discharge from the shear shredder had a much lower organic material content (73.42%) than the hammermill-shredded NSW (86.46%). The difference is made up predominantly by the shear shredded discharge having a higher glass and ferrous content. Additionally, the shear shredder discharge contained more nonferrous metals and inert material than did the hammermill shredder discharge.

The very low glass content in the hammermill discharge may have been related to the fact that glass was pulverized and embedded into the softer organic material by the high impact hammers. Also, it may have indicated the hammermill and shear shredders were fed different types of NSW.

The corresponding size distribution plots of Tables 8 and 9 are shown in Figure 1. The curves are similar except that the hammermill-shredded discharge curve is offset slightly to the right portion of the graph or to finer particle sizes. The size distribution of each compositional category from the total NSW is plotted in Figure 2 (shear shredder), and Figure 3 (hammermill shredder). These figures show the cumulative weight percent passing a sieve size versus the base-10 logarithm of that sieve size. Thus, the total cumulative percent of each category is 100 and the sieve size increases with the abscissa. The offset to slightly finer size for the hammermills shredded material is particularly noticeable in the organics, glass, and inerts curves. All the curves indicate that the hammermill produced a finer discharge particle size.

Figures 2 and 3 are helpful in estimating the characteristic particle sizes and nominal sizes of the various solid waste constituents. The characteristic size is the size of a hypothetical screen through which 63.2 percent of the material would pass and on which 36.8 percent would be retained. It provides a simple description of sample size. The value is related to the Rosin-Rammler (Ref 5) equation which has shown relatively good fit in describing the size distribution of shredded refuse. The nominal size is that size of a screen where 90 percent of the material would pass and 10 percent would be retained. It emphasizes the coarser particle sizes. The nominal size is useful in the design of waste handling processing systems.

Calculated characteristic and nominal particle size values are listed in Table 10. The ratio of total shear-shredded to total hammermill-shredded discharge-material for the characteristic sizes is 1.36, indicating the generally coarser particle size produced by the shear shredder. The same ratio for the nominal size is only 1.11 which suggests that each shredder produces a similar amount of extremely coarse material.

Power Consumption

Power consumption data for the shredders in Charleston, SC, are shown in Table 11. Power was reported for 105 days for the shear shredder and 99 days for the hammermill. Both the weighted average for the period and

the daily average of the shear shredder power consumption were slightly greater than 3 kWh/ton. The weighted average power consumption of the hammermill shredder was 8.44 kWh/ton which was two and one-half times greater than that for the shear shredder. The daily average power consumption of the hammermill was 9.24 kWh/ton.

Operations, Maintenance, and Supervision

Operations and maintenance data were recorded for the Cedarapids 5096 shear shredder and each of the Heil 42-F vertical-shaft hammermills. An operating log was kept to record the hours that the shredder was running and not running. The operating hours were segregated into processing and idling periods. Downtime was segregated into blockage, repair, and no-fault (off-duty) hours. A summary of the shredder operations is given in Table 12.

The total period for this analysis was 1475.7 hours. Each of the shredders during this period processed NSW for about 700 hours or just under 50 percent of the total logged time. The shear shredder was allowed to idle without processing material for a greater portion of the time, 36 percent compared to approximately 20 percent for each hammermill shredder. The difference was almost counterbalanced by the longer no-fault hours of the hammermill shredders. The shear shredder required approximately two percentage points more time for repairs than the hammermill shredder. Blockage time was close to 1 percent for all three shredders.

These data show that all the shredders experienced similar operating histories; however, the shear shredder was often allowed to idle while the hammermills were normally turned off when not shredding. This was because the shear shredder could accept a greater variety of feed material and, because of its lower power demand, was kept in idling reserve more often than the hammermills.

Operations, maintenance, and supervision/other labor were tabulated for each shredder over a 7-month period beginning March 1 and ending September 20, 1984, but the number of days recorded was only 121. Data are summarized in Table 13.

Allocation of labor to specific unit operations of an entire plant is difficult. Usually, the work force is on the job regardless of whether the equipment is operating or not operating. In the case of the Charleston SWRC, County officials determined that during normal shift operations, the shear shredder required 12 man-hours of operating labor, 0.8 man-hour of routine maintenance labor, and 1 man-hour of supervisory labor. For each hammermill the labor breakdown was 11 man-hours for operating, 0.6 man-hour for maintenance, and 1 man-hour for supervising. On Wednesdays, when less NSW was delivered to the SWRC, the operating man-hours were decreased to 8 for the shear shredder and 7 for each hammermill. No adjustments were made to maintenance and supervisory labor on Wednesdays. Only occasional reallocations were made for operational variations.

As shown in Table 13, operations labor was higher for the shear shredder compared to each hammermill. Maintenance labor for the shear shredder was one-third higher than for a hammermill. Supervision labor

was essentially identical for all shredders. Since the shear shredder processed approximately four times the quantity of NSW than either hammermill, the operations, maintenance, and supervision labor per ton of waste processed by the shear shredder was much lower.

Major maintenance actions were considered repairs in this work. To be defined as a major maintenance action the remedy had to be nonroutine, require at least one man-hour of labor, or have parts cost in excess of \$50.00. Examples of repairs for this study include the replacement of filters and cutters for the shear shredder and the replacement of hammers and liners for the hammermill shredders.

Detailed repair labor and parts data were collected and are summarized in Table 14. During the 6-month period, the shear shredder required less labor per ton of refuse processed, but had higher parts cost than the hammermills.

Comparisons With Additional Data

Manufacturers' data list the shear shredder and hammermill capacities at 35 to 60 TPH and 10 to 25 TPH, respectively. As shown in Table 7, the average measured capacities of the shredders excluding idle periods were 69 and 16 TPH, respectively. With idle included, the rates at 38 TPH and 12 TPH were still in the manufacturers' ranges. Therefore, each shredder processed according to its manufacturer's specifications during this study.

Data were also available from a major demonstration program which was funded by the New York State Energy Research and Development Authority (NYSERDA) at Chemung County, New York. That program included a comparative side-by-side study of a Cedarapids 5096 shear shredder and a Jeffrey 790 horizontal-shaft hammermill. As stated before, data in Table 7 were from a Cedarapids 5096 shear shredder and two Heil 42-F vertical-shaft hammermill shredders at Charlerton County, SC. Comparative data from shredders in Charleston County, SC and Chemung County, NY are presented in Table 15. It should be noted that the demonstration test in Chemung County, NY, was on municipal solid waste.

The shear shredder used in that test was variously configured with 6-, 4-, and 2-inch cutters. The Chemung County data were obtained from the averaging of individual transfer trailer loads, while the Charleston County data were the weighted average of production data. Again, the Chemung County data showed that the hammermill shredder produced a finer size of discharge than did the shear shredder.

The Chemung County data also showed that the throughput capacity and average particle size reduced and the power consumption increased as the cutter width for the shear shredder decreased.

Particle size distributions for the four shredder configurations in Chemung County and the two shredder configurations in Charleston County are shown in Figure 4 using logarithms of the sieve sizes. This shows that the shear shredder with 4-inch cutters in Charleston County produced a particle size distribution that was finer than that produced in Chemung County with 4-inch cutters. In other words, the NSW was reduced to smaller particle size than the MSW using the same shear shredder. In fact, the NSW shredded size using 4-inch cutters was closer to the MSW shredded size using 2-inch cutters. Figure 4 also shows that the Jeffrey 790 horizontal shaft hammermill produced the finest particle size distribution.

Although further comparisons between the shredders and shredded discharge materials at the two sites can be made, there is the concern that different feed compositions, operating procedures, and feed systems might have influenced the results.

There are two points to be made. The first is that shear shredders, applied to solid waste shredding, are relatively new. As experience is gained, the cost of cutters per ton processed could be significantly reduced. The improvements could result from metallurgical changes in cutters that extend cutter lives, or improvements in manufacturing techniques that could decrease the cost of cutters. The second point is that a hammermill of comparable capacity to the shear shredder should be tested because most of the parameters from this study are dependent upon the throughput capacity of the mill tested.

RAM Analyses

Reliability, availability, and maintainability (RAM) analyses were determined using Navy procedures (Ref 6) for the shear shredder and the vertical-shaft hammermill shredders. Total monitoring time, T, observed in the RAM analyses is expressed in Equation 1:

$$T = t_{a1} + t_{a2} + t_b + t_c + t_d + t_e \tag{1}$$

where: t_{a1} = Time shredder was energized and processing (operational), hr.

t_{a2} = Time shredder was energized but idle (not processing), hr.

t_b = Time spent in routine maintenance, hr.

t_c = Time spent in repairs/replacements, hr.

t_d = Time shredder was de-energized (down), but operational, hr.

t_e = Time shredder was de-energized (down), but not operational, hr.

The numerical values for the time periods, labor man-hours for each period, and other independent parameters during January through June, 1984 are presented in Table 16. The results of the RAM analyses are presented in Table 17 and are discussed below:

1. Reliability (R). Reliability is the measure of the probability that the equipment functions satisfactorily over the duration of its mission. Reliability can be computed for various missions including waste disposal and steam production. Equation 2 is the simplified form of R:

$$R = e^{-t_m/MTBF} = \frac{1}{\mathrm{Exp}\left(\dfrac{t_m}{ta/N_f}\right)} \tag{2}$$

where: N_f = Number of failures that caused shutdown of the system.

$t_a = t_{a1} + t_{a2}$ = operating time, hr.

t_m = Mission time. This is the time over which we wish uninterrupted operation of the system, hr.

MTBF = Mean time between failure, hr.

The reliabilities were 0.99 for the hammermills and 0.98 for the shear shredder. Thus, the reliabilities of the two types of shredders were nearly the same. Mission time was selected as 8 hours or one operating shift.

2. Availability (A). Availability is defined as the probability that equipment will be capable of performing its specified function when called upon. Operational availability provides the best measure for equipment in an operational environment. It is the ratio of the operating time over the sum of operating time and downtime. Equations 3a and 3b are used to calculate the operational availability (A) for each shredder with and without the idle period, respectively.

$$A = \frac{t_{a1} + t_{a2}}{T} \tag{3a}$$

$$A = \frac{t_{a1}}{T} \tag{3b}$$

As stated previously, the shear shredder was allowed to idle for longer periods while the hammermills were turned off. As a result of this operational practice, the hammermills had higher availability (49.8 percent compared to 47.2 percent) than the shear shredder excluding idle periods. However, the shear shredder had higher availability (82.4 percent compared to 68.9 percent) if the idle time is included.

3. Maintainability (M). Maintainability is expressed as the man-hours required for maintenance and repairs within a given period of operating time. Equations 4a and 4b for calculating maintainability are shown below:

$$M = \frac{M_{tb} + M_{tc}}{t_{a1} + t_{a2}} \tag{4a}$$

$$M = \frac{M_{tb} + M_{tc}}{t_{a1}} \tag{4b}$$

where M = Maintainability, man-hours/hr.

M_{ta} = Man-hours for routine maintenance.

M_{tb} = Man-hours for repairs/replacement.

With or without the idle period included in the operating time, the hammermill shredders required less man-hours for maintenance.

LIFE-CYCLE COST ANALYSIS

Life-cycle cost comparisons based on Navy economics practice were made for the two types of shredders at the Charleston County, SWRC. The analyses calculated the present value (PV) cost and other costs for NSW. The present value cost shown in Table 18 was calculated both including and excluding capital investment (that is, considering the capital cost as a sunk cost). The results of the analysis with the capital investment included showed the cost per ton for shredding to be $2.34 for the shear shredder and $4.62 for the hammermill. With capital investment of the entire facility (including the building, auxiliary equipment, and shredder) excluded, the shear-shredding cost decreased to $1.60/ton while the hammer decreased to $2.46/ton.

The latter approach was the preferred analysis since it appeared to more accurately model the present status of the SWRC. The hammermills were installed as original equipment in the SWRC while the shear shredder was retrofit at a later date, but prior to this program. This made cost comparisons more difficult, unless the capital cost for the entire facility was deleted. In addition, most published data on shredding costs are predominantly operations and maintenance costs, which are comparable to considering the total capital cost as a sunk cost.

Procedure

The analysis utilized the Navy economics procedures contained in Reference 7. A facility life of 25 years and a shredder life of 10 years was selected from the Navy's guidelines. The project life for the life-cycle period was selected as 20 years, or two times the life of the shredder. An allowance was made at the tenth year to replace the shredder. It was anticipated the shredder would not be replaced in year 20 since the facility had only 5 years of service life remaining. Operations and maintenance costs were determined for every year of the 20-year project life observing an inflation rate of 5 percent.

When capital investments were included in the cost analysis, a construction period of 1 year was selected and the capital costs were paid quarterly. The time value of money of construction payments was incorporated into the analyses at an annual discount rate of 10 percent. The present value of all costs for each year of the 20-year life were then calculated for the base year, in this case 1985. A refuse-drived-fuel (RDF) revenue was considered in the analysis for each year of the 20-year project life. A 1985 present value for revenue was also calculated.

Finally, the net present value (cost minus revenues) was calculated and divided by the total production for the 20-year period to arrive at a net present value cost-per-ton calculation.

Cost Estimates

The life-cycle cost analyses were done utilizing the data obtained from this program, other published information, and necessary estimates. The summarized data that were used for both the shear shredder and the hammermill analyses are presented in Table 18. All costs were determined in 1985 dollars and inflated at 5 percent annually for subsequent years.

Operating Costs. Labor rates for solid waste facilities in the general Charleston, SC, area were reviewed. Three categories of labor were used: operations - $7.50/hour; maintenance - $5.25/hour; and administration - $10.50/hour. A burdening factor of 1.25 was applied to each rate to cover fringe benefits. Man-hour per ton labor data developed in the preceding sections (e.g., see Table 14) were used in the analyses.

Operating costs for the Charleston shredding operation were dominated by electrical power costs for both shredders, and replacement costs of blades and hammers for the shear shredder and hammermills, respectively. The electrical power cost in the Charleston area was approximately $0.06/kWh. Power consumption data, measured in this program for each shredder, were used. Cutter blades cost $24,000 per set for the shear shredder and hammers cost $9.00 apiece for the vertical-shaft mills. The repair parts costs-per-ton, calculated in Table 14 in this report for each shredder, were employed in the life-cycle cost analyses.

Disposal costs for Charleston County are approximately $8.60/ton. A value of $1.00/ton was utilized in this particular analysis, however, to represent the differential cost between shredded and unshredded solid waste disposal at the landfill. In Charleston County, both shredded and unshredded solid waste is landfilled. The unshredded waste requires more landfill volume and more cover material. This has been estimated as having an added cost impact of $1.00/ton on the unprocessed waste. Since all the material is landfilled, no value can be assigned to the RDF produced.

Availability of the shredders, as determined on this project, was applied to annual shredder production figures. This was accomplished by utilizing shredder throughput rates, idle, blockage, and repair hours in the calculation. Thus, processing rates employed in the cost analyses were 35.75 TPH and 10.66 TPH for the shear shredder and each of the hammermill shredders, respectively.

Capital Costs. The preferred analyses did not include capital costs and considered the cost of the facility as a sunk cost (all capital costs added to zero). In the case when capital costs were included, the costs consisted of equipment and materials (E&M), installation, engineering and construction supervision, and management reserve. The E&M costs totaled $607,440 for the shear shredder plant and $412,500 for the twin hammermill shredder plant; installation costs totaled $217,840 for the shear shredder

and $249,520 for the hammermills; engineering and construction supervision was estimated at 12 percent of the installation costs; and a management reserve at 15 percent of the installation costs. Contingency costs for each shredder were calculated as 25 percent of the sum of the total capital costs. The equipment cost in 1985 dollars was also inflated to 1995 dollars at 5 percent to determine the equipment replacement cost in year 10. The present value of that cost was calculated for year zero of the project life.

As shown in Table 18, the shear shredder involved a greater capital investment but with a corresponding larger production of shredded product. The resultant present value of unit capital cost for the shear shredder was only $0.87 per ton, while that for the hammermill facility was $2.35 per ton. The costs for the shredders were estimated at $300,000 for the shear shredder and $87,000 for each of the hammermills. The ratios of the total equipment and materials to the shredder costs were 2.02 for the shear shredder and 4.74 for the hammermill. If infeed and discharge conveyors were in existence and conveyor costs (estimated at $214,000 in both cases) were excluded from the facility equipment costs, then the ratios of the total equipment and materials to the shredder costs would decrease to 1.31 for the shear shredder and 2.28 for the hammermill. The extremely low ratio for the shear shredder has been calculated (Ref 8) and supported by manufacturers (Ref 9,10). They indicated that, in the more complex installations, a factor of 25 to 30 percent additional to the cost of the shear shredder should safely cover the ancillary equipment. For simple installations with existing conveyors, the cost ratios can be much lower. Typically, the shear shredder price includes a stand, feed hopper, and local control panel; the only additional material costs are for transition chutes, anchor bolts, grouting, electrical connections, and control wiring.

Sources of capital cost data include Chemical Engineering Magazine, Charleston County Shredder Explosion Insurance Claim Report, Allen Bradley Catalogue data, actual and calculated data from this project, and engineering estimates.

Cases With and Without Initial Capital Cost

As stated above, the preferred case is where there are no capital costs and the first day of operations is set at day zero of the project life. In this case, the present value of the major equipment (shredder) replacement shown in Table 18 was lower for the hammermill. However, the shear shredder processed 1,426,420 tons of solid waste while the hammermill could process only 426,400 tons over the 20-year period. Hence, the present value cost per ton was $1.60 for the shear shredder and $2.46 for the hammermill.

The same comparative situation prevailed when the initial capital was included and the first day of construction was set as day zero, or the reference day. The project life became 21 years: 20 were processing years and the other year was the construction period. With this small variation, the present value of equipment costs and operations and maintenance costs were slightly less than those for the previous case, but the PV ratios between the shredder types were identical. Major equipment costs were $442,200 for shear shredder and $299,190 for hammermill. Once again, the 20-year production capacity of the shear

shredder was over three times that of the hammermill. The resultant net present value for the shear shredder on a per-ton basis was lower for the shear shredder, $2.34 compared to $4.62.

The life-cycle cost analyses for the Charleston County SWRC parallel those findings in the Equipment Performance section. On a cost-per-ton basis, the shear shredder costs are also lower than the hammermill shredder costs.

CONCLUSIONS

Based on the data and results presented above, we can draw the following conclusions:

1. The composition of NSW is similar to that of MSW except that the former has more organics and contains less than 0.5 weight percent of flammable or explosive materials.

2. Using the same size of shear shredder, NSW can be reduced to smaller particles than MSW.

3. The performances of the shear shredder and the hammermill shredder show a number of significant differences as follows:

- Feed Limitations - The shear shredder results in a smaller amount of unshreddable and difficult-to-shred materials than the hammermill shredder.

- Discharge Size - The hammermill shredder produces a discharge of somewhat finer solid size than the shear shredder at both Charleston and Chemong Counties.

- Power Draw - The electricity consumption of the shear shredder per unit solid weight processed is less than that of the hammermill shredder (3.02 versus 8.44 kWh/ton, respectively).

- Labor Needs - The unit labor requirements for operations, maintenance, and management for the shear shredder are less than those for the hammermill shredder. The former requires 0.035, 0.003 and 0.003 man-hours/ton for the above three items, respectively, while the latter needs 0.133, 0.008, and 0.013 man-hours/ton, respectively.

- Repair Costs - The shear shredder requires less repair labor but higher part costs than the hammermill shredder.

- Reliability - The shear shredder and the hammermill shredder have nearly the same reliability without interruption in operation. However, the shear shredder exhibits a higher operational availability (based on the total operational time) but a poorer maintainability. This is because the

shear shredder is allowed to idle for longer periods within operational time. The idle is justified by the larger processing capacity and smaller power consumption of the shear shredder.

- Total Costs - The shear shredder has a significant economical advantage over the hammermill shredder. When capital investment for existing facilities is excluded, the net present values of total costs become $1.60/ton and $2.46/ton for the shear shredder and the hammermill shredder, respectively. When capital investment for new facilities is included, the net present values of total costs are $2.34/ton and $4.62/ton for the two types of shredders, respectively.

- Operating Costs - Similarly, when capital investment is not required, the present values of operating costs are $1.60/ton and $2.46/ton for the shear shredder and hammermill shredder, respectively. When capital investment is required, the net present values of operating costs are $1.40/ton and $2.27/ton for the two types of shredders, respectively.

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NOMENCLATURE

A	Availability, fraction
E&M	Equipment and materials
kWh/ton	Kilowatt-hour/ton
lb/cu.yd.	Pound per cubic yard
M	Maintainability, man-hours/hr
MSW	Municipal solid waste
MTBF	Mean time between failure
M_{ta}	Man-hours during period t_a
M_{tb}	Man-hours during period t_b
M_{tc}	Man-hours during period t_c
NA	Not available
NAVFAC	Naval Facilities Engineering Command
NPV	Net present value
NYSERDA	New York State Research and Development Authority
NCEL	Naval Civil Engineering Laboratory
N_f	Number of failures
N_r	Number of repairs
O&M	Operations and maintenance
PV	Present value
R	Reliability, fraction
RAM	Reliability, availability, and maintainability
RDF	Refuse derived fuel
NSW	Navy solid waste
SWRC	Solid waste reduction center

TPD	Tons per day
TPH	Tons per hour
rpm	Revolutions per minute
T	Total monitoring time, hour
t_a	Operational time, hour
t_{a1}	Operational time when shredder was energized and processing, hour
t_{a2}	Operational time when shredder was energized but idle (not processing), hour
t_b	Routine maintenance time, hour
t_c	Repair time, hour
t_d	Time when shredder was de-energized (down) but operational, hour
t_e	Time when shredder was de-energized (down) but not operational, hour
t_m	Mission time, hour

Table 1. Comparison of Shredders

Item	Cedarapids 5096	Heil 42-F
Overall dimensions, L x W x H (in)	175 x 74 x 52	133 x 124 x 118
Infeed opening (in)	50 x 96	36 x 66
Weight (lb)	40,000	25,000
Shafts	2 - horizontal	1 - vertical
Motor horsepower	2 x 200	1 x 250
Drive	Hydraulic	V-Belt and Sheave
Shaft RPM	1 - 33 1 - 43	1200 nominally, both clockwise and counter
Cutters/Hammers weight (lb)	24 cutters 400, approximately	38 hammers 14.25
Tip to tip distance (in)	26	from 27 to 42 depending on location
Procedure for difficult-to-shred	Reverse, or jam and remove manually	Reject, or jam and remove manually
Rated capacity (TPH)	35 - 60	10 - 25

Table 2. Analysis of Navy Waste Sample

Truck Bulk Density and Composition

Volume, ft^3	10800
Usage	0.88
Net volume, ft^3	9450
Density, lb/ft^3	
Average	5.05
Weighted average	5.18

Item	Total Sample	
	Wet Weight (lb)	Wet Weight (%)
Composition		
Paper	13139	26.86
Plastic		
Light	2036	4.16
Heavy	237	0.48
Other	117	0.24
Rubber		
Tires	2	.00
Other	665	1.36
Cardboard	13973	28.56
Textiles	860.5	1.76
Wood		
Pallets	2140	4.37
Other	3556	7.27
Misc. organics	10755	21.99
Subtotal organics	47480.5	97.06
Glass	330.5	0.68
Inerts/ceramics	266	0.54
Subtotal Inerts	596.5	1.22
Ferrous		
Cable/strapping	83	0.17
Other	351	0.72
Subtotal ferrous	434	0.89
Nonferrous		
Cable	29	0.06
Other	242	0.49
Subtotal nonferrous	271	0.55
Miscellaneous		
Aerosol can	7	0.01
Paint	4	0.01
Solvents	10	0.02
Oil	15	0.03
Insulation	100	0.20
Subtotal miscellaneous	136	0.28
TOTAL	48918	100.00

Table 3. Estimated Densities and Statistics by Waste Types

Waste Type	Density (lb/yd^3)	Standard Error (lb/yd^3)	95% Confidence Interval (lb/yd^3)[a]	Student's t-Value
Paper	56	7.5	41-70	7.4
Cardboard	44	6.4	31-56	6.8
Mixed office	75	3.3	68-81	22.9
Residential	98	8.8	81-116	11.2
Wood	158	16.7	126-191	9.5
Yard	138	13.8	111-165	10.0
Food	477	29.3	419-535	16.3
Metals	117	66.6	-14-248	1.8[b]
Dormitory	56	10.7	35-77	5.3
Sewage	333	195.9	-52-717	1.7[b]
Glass	712	1052	-1354-2778	0.7[b]
Ship	290	91.7	110-470	3.2
Construction	850	706	-536-2236	1.2[b]

[a] The statistical 95% confidence limits about the estimated densities are shown on this table. These confidence limits assume that the densities are normally distributed. This is not strictly true because it is theoretically impossible for a density to be less than zero. The violations of the normality assumption are expected to be most severe when the estimated density is close to zero or when its standard deviation is large. In either of these cases the lower confidence limit, based on the normal distribution, may be less than zero.

[b] A student's t-test, using a significance level of 0.05, was used to determine if the estimated densities are statistically significant. Accordingly, t-values of less than 1.9 are not statistically significant. Thus, density values associated with such t-values are considered unreliable for use in this model.

Table 4. Estimation of Weighted Average Density Using Type Densities

Observed weighted-average density (from Table 2):

$$5.18 \frac{lb}{ft^3} * \frac{27\ ft^3}{1\ yd^3} = 139 \frac{lb}{yd^3}$$

Estimated weight average density:

Waste Type	(a) Wt. fract. from Table 2	(b) Type density (lb/yd^3) from Table 3 & Ref 4	(a) x (b)
Paper	.2686	56	15.04
Plastics	.0488	109[b]	5.32
Rubber	.0136	218[b]	2.96
Cardboard	.2856	44	12.57
Textiles	.0176	109[b]	1.92
Wood	.1164	158	18.39
Miscellaneous organics	.2199	197[a]	43.32
Inert and glass	.0122	712	8.69
Metals	.0144	117	1.68
Miscellaneous	.0028	117	0.33
	1.0000		110.23

Calculated weighted-average density = 110.23 lb/yd^3.

[a]Average density of solid wastes from mixed office, residential, yard, and food.

[b]Data from Reference 4.

Table 5. Comparison of Composition of Navy Solid Waste and Municipal Solid Waste.

Composition	NSW Weight (%)		MSW Weight (%)	
	From Table 2	From Ref 3	Medium[a]	Normalized
Paper	26.86	53.4	50	
Plastic	4.88	1.0	6	
Rubber	1.36	0.1	1	
Cardboard	28.56	30.0	-	
Textiles	1.76	-	2	
Wood	11.64	4.0	3	
Other organics (food, leather)	21.99	8.3	16	
Organics	97.06	96.8	78	67.83
Inerts/glasses	1.22	1.1	10	8.69
Metals	1.44	2.0	9	7.83
Miscellaneous	0.28	0.1	18	15.65
Total	100.00	100.0	115	100.00

[a]Medium values from Reference 2.

Table 6. Unshreddable and Difficult-to-Shred Objects of Navy Solid Waste (data are in pounds)

Component		Unshreddable		Difficult-to-Shred	
		Shear	Heil	Shear	Heil
Paper	13139	0	0	0	360
Plastic					
Light	2036	0	0	0	0
Heavy	237	0	0	0	0
Other	117	0	0	0	0
Rubber					
Tires	2	0	0	0	0
Other	665	0	430	0	0
Cardboard	13973	0	1540	0	605
Textiles	860.5	0	62	62	75
Wood					
Pallets	2140	0	1715	0	95
Other	3556	0	1224	0	1125
Misc. organics	10755	0	0	0	0
Glass	330.5	0	0	0	0
Inerts/ceramics	266	0	0	0	60
Ferrous					
Cable/strapping	83	0	0	0	0
Other	351	0	100	40	77
Nonferrous					
Cable	29	0	0	0	0
Other	242	19	19	0	12
Miscellaneous					
Aerosol can	7	0	2	0	0
Paint	4	0	0	0	0
Solvent	10	0	1	0	0
Oil	15	0	0	0	0
Insulation	100	0	0	0	0
Total	48918	19	5093	102	2409
Percent	100.00	0.04	10.41	0.21	4.92

Table 7. Processing Capacity of Shredders

Item	Shear Shredder	Vertical Hammermills		
	Mill #1	Mill #2	Mill #3	Combined
Days tested	165	157	157	157
Tonnage (w)	48,709	11,877	11,763	23,640
Daily tonnage				
Average	295.21	75.65	74.92	150.57
Maximum	488.0	153.0	147.0	295.00
6-month operations records				
a. Process hours	706.6	732.7	683.6	1416.3
b. Idle hours	533.2	277.7	313.8	591.5
c. Blockage hours	10.5	11.2	27.3	38.5
d. Repair hours	112.3	84.2	87.3	171.5
e. No-fault hours	113.1	369.9	363.7	733.6
6-month shredder capacity, TPH				
a. w/a above	68.93	16.21	17.81	16.69
b. w/a and b	39.29	11.75	11.79	11.77
c. w/a, b, and c	38.96	11.63	11.48	11.55
d. w/a, b, c and d	35.75	10.74	10.58	10.66
e. w/a, b, c, d and e	33.01	8.05	7.97	8.01
Average of daily capacities, TPH				
a. Process hours, only	68.16	16.02	17.41	16.33
b. Process and idle hours, only	37.95	11.61	12.01	11.52
Peak daily capacity, TPH				
a. Process hours, only	114.29	42.92	47.69	38.33
b. Process and idle hours, only	62.00	21.51	47.50	32.86

NOTE: All data were for an 8-month period.

Table 8. Shear Shredder Size Distribution -- Average Data (inches)

	12	8	6	4	2	1	1/2	1/4	1/8	PAN	TOTAL
Paper	0.00	0.13	0.89	7.83	6.71	2.83	0.99	0.23	0.04	0.00	19.65
Plastic	0.00	0.24	3.69	2.98	3.26	1.54	0.61	0.28	0.10	0.00	12.70
Cardboard	0.00	1.51	1.50	5.48	4.33	2.12	0.80	0.19	0.01	0.00	15.95
Textiles	0.00	0.83	0.47	1.09	1.30	0.46	0.23	0.07	0.00	0.00	4.44
Wood	0.00	0.00	0.41	0.57	1.53	1.27	0.74	0.45	0.22	0.00	5.19
Other	0.00	0.00	0.18	0.62	0.83	1.81	2.57	2.20	1.76	5.51	15.48
TTL Organic	0.00	2.71	7.13	18.57	17.97	10.03	5.95	3.41	2.14	5.51	73.42
Glass	0.00	0.00	0.00	1.03	1.72	2.72	3.05	2.18	0.57	0.20	11.47
Inerts	0.00	0.00	0.00	0.00	0.57	0.64	0.77	0.66	0.98	2.20	5.83
TTL Inert	0.00	0.00	0.00	1.03	2.29	3.36	3.83	2.84	1.55	2.40	17.30
Ferrous	0.00	0.00	1.04	1.03	2.56	1.36	0.38	0.14	0.07	0.05	6.62
Nonferrous	0.00	0.00	0.00	0.23	1.67	0.51	0.21	0.02	0.02	0.00	2.66
TTL Metals	0.00	0.00	1.04	1.26	4.23	1.87	0.59	0.17	0.09	0.05	9.28
Total, Wt.%	0.00	2.71	8.17	20.86	24.49	15.26	10.36	6.42	3.78	7.96	100.00

Table 9. Hammermill Size Distribution - Average Data (inches)

	12	8	6	4	2	1	1/2	1/4	1/8	PAN	TOTAL
Paper	0.00	0.00	0.77	4.00	6.99	9.62	4.49	2.23	0.17	0.00	28.29
Plastic	0.53	1.05	1.34	3.38	2.60	2.05	1.96	0.88	0.19	0.00	13.98
Cardboard	0.00	0.25	1.20	6.57	5.81	4.83	2.06	0.52	0.22	0.00	21.47
Textiles	0.71	1.31	0.07	0.66	2.04	0.92	0.47	0.09	0.00	0.00	6.27
Wood	0.00	0.00	0.00	0.40	0.62	0.41	0.56	0.20	0.00	0.00	2.20
Other	0.00	0.00	0.00	0.02	0.43	1.11	1.48	1.59	3.89	5.74	14.26
TTL Organic	1.23	2.61	3.39	15.02	18.50	18.94	11.03	5.52	4.47	5.74	86.46
Glass	0.00	0.00	0.00	0.00	0.02	0.47	1.26	1.81	0.22	0.10	3.88
Inerts	0.00	0.00	0.00	0.00	0.00	0.11	0.17	0.32	2.52	1.87	4.99
TTL Inert	0.00	0.00	0.00	0.00	0.02	0.58	1.43	2.13	2.74	1.97	8.87
Ferrous	0.00	0.00	0.00	0.53	1.94	0.63	0.34	0.18	0.04	0.04	3.71
Nonferrous	0.00	0.00	0.00	0.15	0.45	0.18	0.12	0.05	0.01	0.00	0.96
TTL Metals	0.00	0.00	0.00	0.68	2.39	0.81	0.46	0.23	0.05	0.04	4.66
Total, Wt.%	1.23	2.61	3.39	15.70	20.91	20.34	12.92	7.88	7.26	7.75	100.00

Table 10. Characteristic and Nominal Particle Size for Shredded NSW in Charleston, SC

Component	Characteristic Size (in)		Nominal Size (in)	
	Shear	Heil	Shear	Heil
Paper	4.2	2.3	5.6	4.9
Plastic	5.0	4.4	7.4	7.7
Cardboard	4.7	4.0	7.2	5.7
Textiles	5.0	3.2	11.5	10.4
Wood	2.2	1.9	4.1	6.3 (est)
Other organics	0.5	0.2	1.9	1.0
Total organics	4.1	2.8	6.8	5.9
Glass	1.3	0.6	3.8	1.0
Inerts	0.3	0.2	1.7	0.2
Ferrous metal	3.5	3.1	6.5	4.9
Nonferrous metal	2.9	2.8	3.9	4.5
Total	3.4	2.5	6.2	5.6
Ratio of total refuse	1.36		1.11	

Table 11. Power Consumption by Shredders

Item	Shear Shredder Mill #1	Vertical Hammermill Mill #3
Days recorded	105	99
Power consumption, kWh for 5 months	100,000	66,400
Quantity processed, tons for 5 months	33,098	7,866
Power to quantity ratio, kWh/ton for 5 months weighted average	3.02	8.44
Daily power consumption, kWh/ton: Average	3.14	9.24
Maximum	6.90	36.36

Table 12. Summary of Shredder's Operating Logs

Item	Running Time		Downtime			Total
	Processing	Idle	Blockage	Repairs	No Fault	
Shear shredder, hours	706.6	533.2	10.5	112.3	113.1	1,475.7
Heil 42-F (#2), hours	732.7	277.7	11.2	84.2	369.9	1,475.7
Heil 42-F (#3), hours	683.6	313.8	27.3	87.3	363.7	1,475.7
Shear shredder, %	47.89	36.13	0.71	7.61	7.66	100
Heil 42-F (#2), %	49.64	18.82	0.76	5.71	25.07	100
Heil 42-F (#3), %	46.32	21.26	1.85	5.92	24.65	100

Table 13. Operations, Maintenance, and Supervision Labor Requirements for Shredding (7-month period)

Item	Shear Shredder	Vertical Hammermills		
	Mill #1	Mill #2	Mill #3	Combined
Days recorded	121	121	121	121
Quantity processed, tons	38,634	9,351	9,262	18,613
Recorded labor, man-hours				
Operations	1,359.5	1,232.3	1,236.8	2,469.1
Maintenance	99.4	77.4	76.4	153.8
Supv/Other	122.0	120.0	120.0	240.0
Calculated labor, man-hours/ton				
Operations	0.0352	0.1318	0.1335	0.1327
Maintenance	0.0026	0.0083	0.0082	0.0083
Supv/Other	0.0032	0.0128	0.0130	0.0129

Table 14. Summary of Repair Actions
(6 month period)

Item	Shear Shredder	Vertical Hammermills		
	Mill #1	Mill #2	Mill #3	Combined
NSW processed, tons	32,681	8,138	8,049	16,187
Repair time, hours	40.7	23.5	24.5	48
Repair labor, man-hours	91	65.5	67.5	133
Repair parts cost, $	49,540	5,054	5,098	10,152
Repair labor, man-hours/ton	.0028	.0080	.0084	.0082
Repair parts cost, $/ton	1.51	0.62	0.63	0.63

Table 15. Comparison of Shredder Processing Information

Item	Charleston County		Chemung County			
	4-in Shear Shredder #1 Mill	Heil Vertical Hammermill #2 & #3 Mills	Cedarapids Shear Shredder			Jeffrey Horizontal Hammermill
			6-in	4-in	2-in	
Capacity (tons/hr)						
Average w/idle	39.3	11.8	43.8	42.4	24.4	47.1
Average w/o idle	68.9	16.7	55.4	49.6	33.3	49.6
Peak w/o idle	114.3	38.3	93.9	90.3	41.1	67.8
Discharge material particle size (in)						
Characteristic size	3.4	2.5	5.5	4.2	3.4	1.9
Nominal size	6.2	5.6	14.3	7.2	5.7	5.6
Power demand (kW)	-	-	118	120	123	90-240
Power consumption (kWh/ton)	3.02	8.44	2.7	2.9	5.1	5.1

SOURCE: Charleston County data from January 1, 1984 - September 20, 1984.
Chemung County data from NYSERDA Program, 1983.

Table 16. Values of Parameters for RAM Analyses

Parameters	Shear Shredder	Vertical-Shaft Hammermill	
	Mill #1	Mill #2	Mill #3
Time, hours			
t_{a1}	484.2	524.1	497.3
t_{a2}	360.6	187.1	204.4
t_b	66.8	43.2	45.2
t_c	47.7	32.8	44.0
t_d	65.9	238.0	234.3
t_e	0	0	0
Labor, man-hours			
M_{ta}	876.5	792.3	796 8
M_{tb}	62.2	49.5	48.5
M_{tc}	91.0	65.5	67.5
M_{td}	NA	NA	NA
M_{te}	0	0	0
Other			
Tons	32,861	8,138	8,049
N_f, No. of Failures	2	1	0
N_r, No. of Repairs	23	23	23

Table 17. RAM Analyses Results for Charleston County Shredders

Parameter	Status	Shear Shredder	Vertical-Shaft Hammermill		
		Mill #1	Mill #2	Mill #3	Combined
<u>Reliability</u>					
R (let Tm = 8)	w/o idle	0.97	0.98	--	0.99
	w/idle	0.98	0.99	--	0.99
<u>Availability</u>					
A	w/o idle	0.4723	0.5112	0.4851	0.4981
	w/idle	0.8240	0.6937	0.6845	0.6891
<u>Maintainability</u>					
M, man-hours/hour	w/o idle	0.3164	0.2194	0.2333	0.2262
	w/ idle	0.1813	0.1617	0.1653	0.1635

Table 18. Life-Cycle Cost Analysis for Shredding at the SWRC

Case	Shear Shredder	Hammermill
Expected Case		
(capital costs are sunk costs):		
PV of original capital costs	0	0
PV of major equipment replacement cost	463,260	313,440
PV of repair, O&M, and disposal costs	1,830,000	737,000
Subtotal present value costs	2,293,260	1,050,440
PV of 20-year RDF revenue	0	0
Net present value cost	2,293,260	1,050,440
20-year production, tons	1,426,420	426,400
NPV of total cost per ton	$1.60	$2.46
NPV of operating costs per ton	$1.60	$2.46
Alternative Case		
(capital costs are included):		
PV of original capital costs	1,249,650	1,002,420
PV of major equipment replacement cost	442,200	299,190
PV of repair, O&M, and disposal costs	1,660,000	670,000
Subtotal present value costs	3,351,850	1,971,610
PV of 20-year RDF revenue	0	0
Net present value cost	3,351,850	1,971,610
20-year production, tons	1,426,420	426,400
NPV of total cost per ton	$2.34	$4.62
NPV of operating costs per ton	$1.47	$2.27

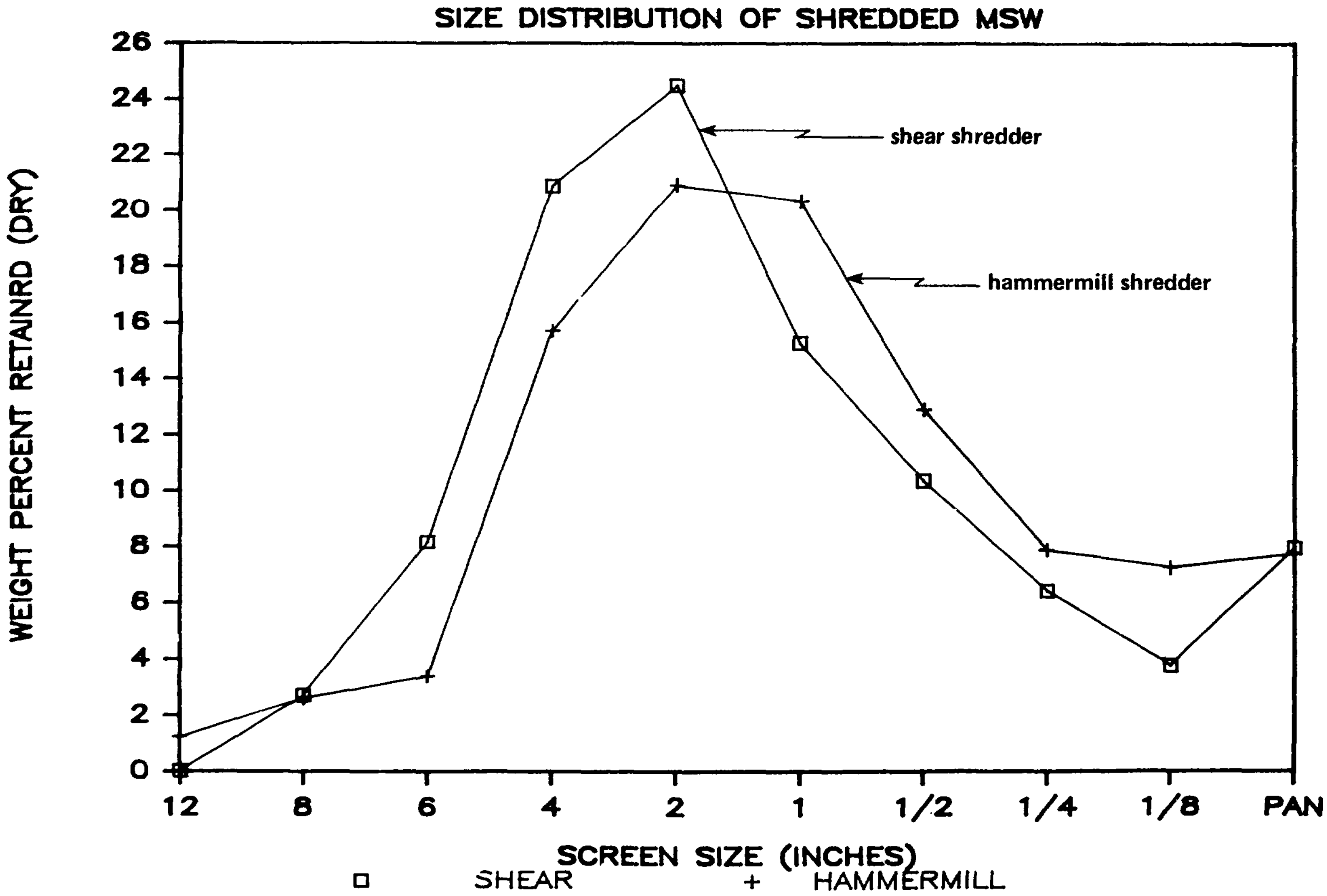

Figure 1. Comparison of shredder products.

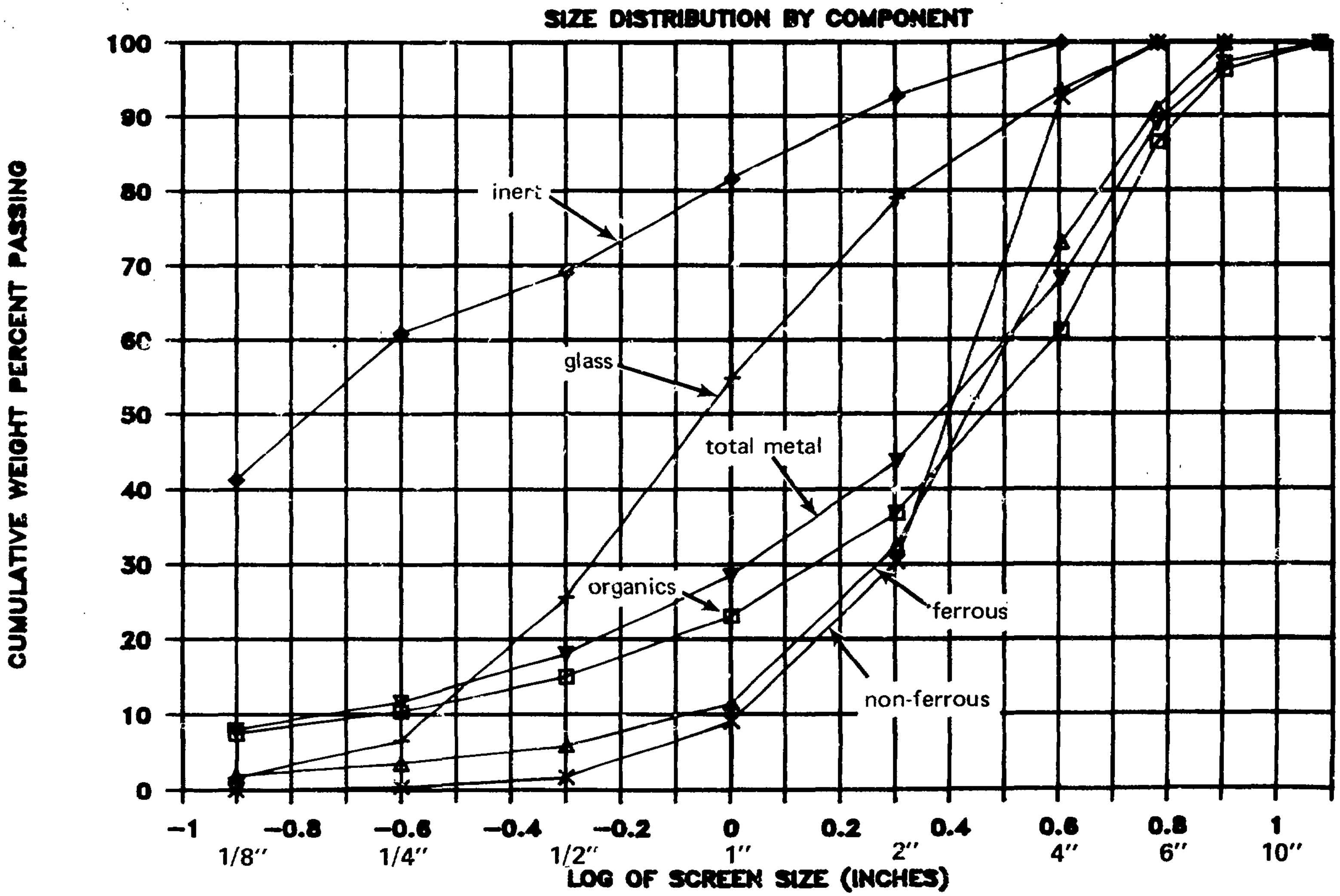

Figure 2. Shear shredder discharge.

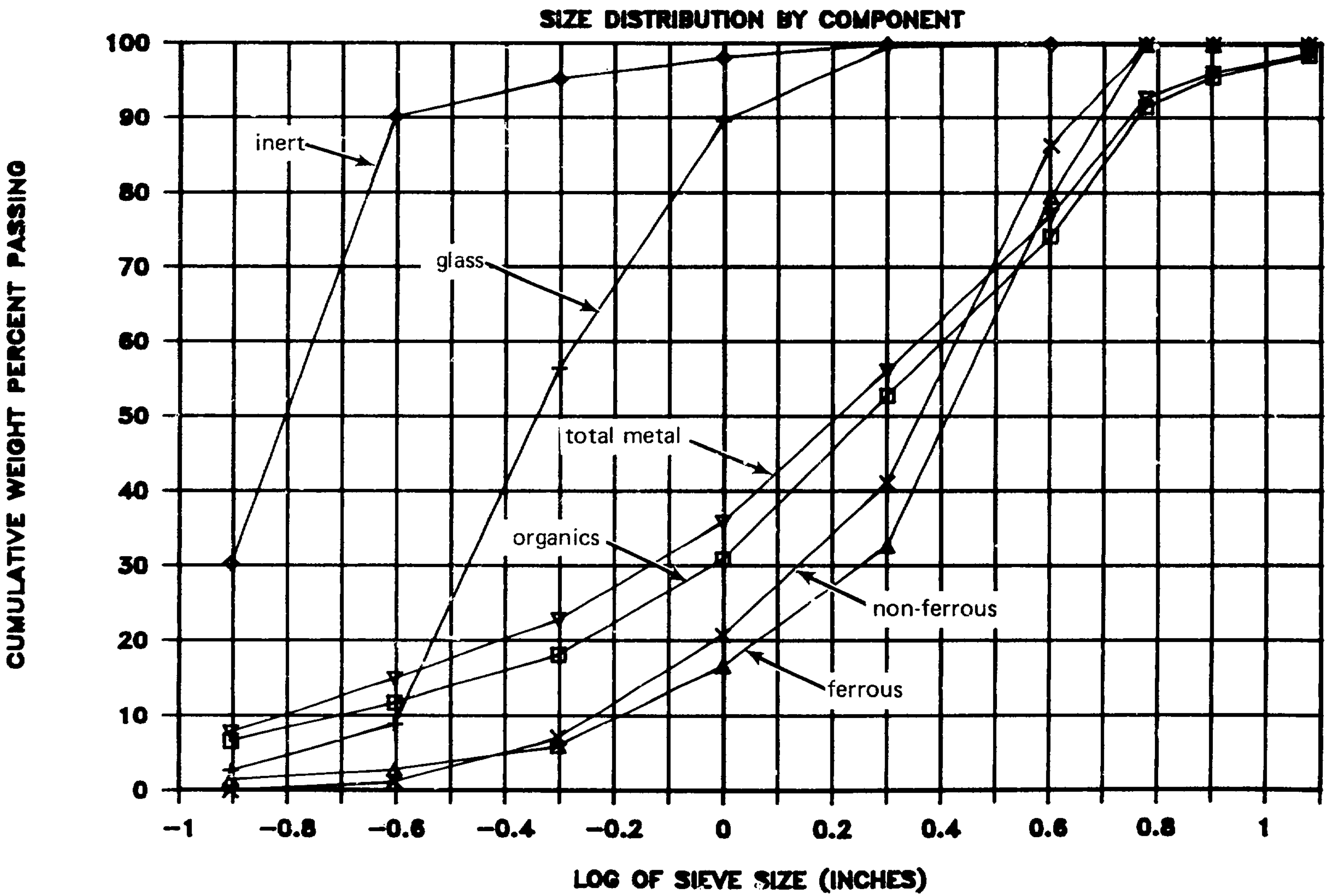

Figure 3. Hammermill shredder discharge.

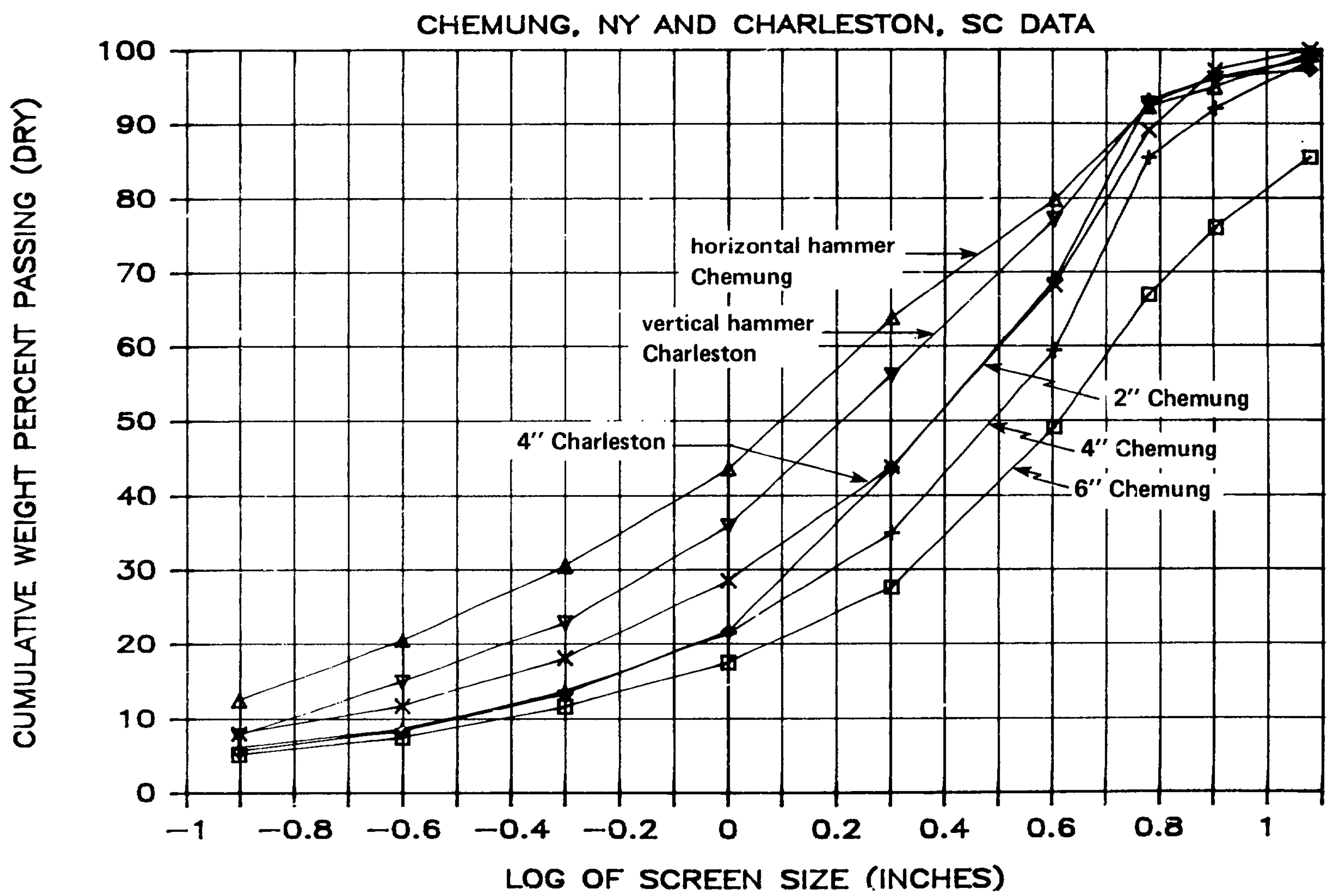

Figure 4. Size comparison of shredded discharge.

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